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Net global warming potential and greenhouse gas intensity of annual rice–wheat rotations with integrated soil–crop system management

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ABSTRACT

The impact of management practices on the net global warming potential (GWP) and greenhouse gas intensity (GHGI) of rice cropping systems is not well documented. A field experiment was established in 2009 to gain insight into the net ecosystem carbon budget and the net GWP and GHGI on the crop seasonal scale over two cycles of rice–wheat rotations. With the local farmer's practices (FP) as the control, three integrated soil–crop system management (ISSM) practices at different nitrogen (N) application rates were established – ISSM-N1, ISSM-N2 and ISSM-N3 – for improvement of rice yield and agronomic nitrogen use efficiency (NUE). Compared with the FP, the rice yields significantly increased by 8.2%, 18% and 31%, while the agronomic NUE increased by 68%, 74% and 99% for ISSM-N1, ISSM-N2 and ISSM-N3, respectively. Within the three ISSM practices averaged over the two cycles, the soil organic carbon sequestration potentials, CH_4 and N_2O emissions were estimated to be 0.089–0.67 t C ha^{-1} yr^{-1}, 166–288 kg CH_4—C ha^{-1} yr^{-1} and 4.27–5.47 kg N_2O—N ha^{-1} yr^{-1}, respectively. Compared to the net GWPs (8.36 t CO_2eq ha^{-1} yr^{-1}) and GHGI (0.58 kg CO_2eq kg^{-1} grain) from the FP, the ISSM-N1 and ISSM-N2 reduced both the net GWPs and GHGIs to some extent, indicating that GHG mitigation can be simultaneously achieved with improved food production and NUE. Although it produced similar GHGIs, the ISSM-N3 increased the net GWPs by 16% compared to the FP, indicating that more research is required on ISSMs for mitigating GHGs to further increase the grain yield and NUE in rice agriculture.

1. Introduction

Rapid population growth and economic development have increased the need for food production around the world (Barrett, 2010). Chinese agriculture has intensified greatly since the early 1980s within a limited land area with large inputs of chemical fertilizers (Ju et al., 2009; Makino, 2011). Because a high proportion of applied nitrogen (N) is lost to the environment (Erisman et al., 2008), large inputs of N fertilizer and low N use efficiency are causing serious environmental problems in the intensive agricultural regions of China (Ju et al., 2009).

With approximately 130 million hectares of rice paddies, China accounts for approximately 31% of the global rice production (Frolking et al., 2002). Summer rice-upland crop annual rotation is a dominant cropping system in the Taihu Lake region in the central Yangtze River Delta. In these rotations, basal N fertilizer was typically applied in a large amount (Zhao et al., 2009). At the conventional application rate of 550 kg N ha^{-1} yr^{-1} (250 kg N ha^{-1} for wheat and 300 kg N ha^{-1} for rice), the nitrogen use efficiency (NUE) was very low (31% for rice and 33% for wheat) (Huang and Tang, 2010). Thus, integrated soil–crop system management (ISSM) has been advocated and developed in China to increase crop productivity and NUE (Chen et al., 2011; Zhang et al., 2011).

However, the overall impacts of different ISSM practices on net global warming potential (GWP) are unknown (Chen et al., 2011; Zhang et al., 2011). The balance among the net exchanges of CO_2, N_2O and CH_4 constitutes the net GWP (Mosier et al., 2006). The agricultural practices can be related to GWP by estimating net GWP per tone of crop yield and is referred as greenhouse gas intensity (GHGI) (Li et al., 2006; Mosier et al., 2006; Shang et al., 2010). Future sustainable agriculture should explore systems with low net GWP and GHGI at high crop productivity for food security. The overall impacts of different ISSM practices on net GWP and GHGI have not been assessed.

Paddy fields have a high capacity for soil carbon sequestration (Lu et al., 2009; Pan et al., 2004; Shang et al., 2010; Zheng et al.,

Abbreviations: F-D-F-M, flooding-midseason drainage-re-flooding-moist irrigation; FP, conventional farmer's practices; GWP, global warming potential; GHGs, greenhouse gases; GHGI, greenhouse gas intensity; GPP, gross primary production; ISSM, integrated soil–crop system management; NECB, net ecosystem carbon budget; NEP, net ecosystem production; NPP, net primary production; Re, ecosystem respiration; SOC, soil organic carbon.

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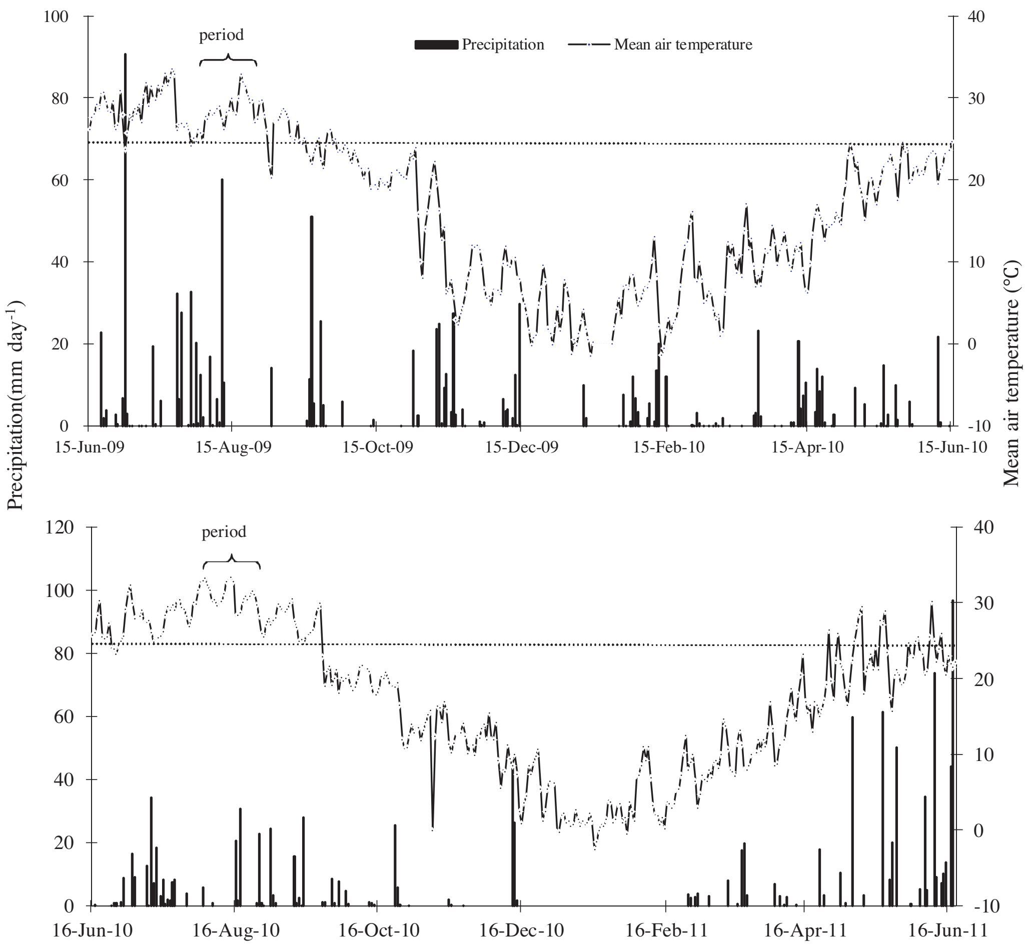

Fig. 1. Daily mean air temperature and precipitation during the two cycles of rice–wheat rotations in 2009 and 2010 in Changshu, China. The period indicated by the arrows refers from rice elongation to the heading stage.

2008). The soil carbon sequestration, i.e., net exchanges of CO_2, could be measured by soil organic carbon (SOC) changes over a subdecadal or decadal timescale (Pan et al., 2004; Shang et al., 2010); the method is not sensitive enough to detect seasonal or annual changes (Zheng et al., 2008). A chamber-based technique has been adopted by Burkart et al. (2007) and Zheng et al. (2008) for the daily net ecosystem CO_2 exchange. The net ecosystem carbon budget (NECB) can essentially provide a scientific basis for the development of carbon sequestration strategies (Chapin et al., 2006; Smith et al., 2010). A simplified chamber-based technique for deriving SOC change from NECB on the crop seasonal time scale was examined in our previous report on vegetable cropping systems (Jia et al., 2012). Here, we conducted intermittent chamber measurements for a typical rice–wheat annual rotation to assess SOC changes on the crop seasonal time scale for the different ISSMs.

Thus, our objectives were to investigate the impacts of different ISSM practices on (1) crop yield and NUE, (2) CH_4 and N_2O emissions, (3) SOC changes derived from the NECB, and (4) net GWP and GHGI in the first two cycles of rice–wheat annual rotations.

2. Materials and methods

2.1. Experimental sites

A field experiment was established at the Changshu agro-ecological experimental station (31°32′93″N, 120°41′88″E), Chinese Academy of Sciences, Jiangsu province. The main cropping system is flooded rice (*Oryza sativa* L.) and drained wheat on an annual rotation. The soil is classified as an *Anthrosol* developed from lacustrine sediment, having silt clay texture. The soil at 0–20 cm depth has a pH of 7.35, a total N content of 2.1 g N kg^{-1}, and an organic C content of 20.3 g C kg^{-1}. The daily mean air temperatures and precipitation during the experimental cropping seasons are collected from Changshu station, which is 100 m away from our experimental site shown in Fig. 1.

2.2. Field plot treatment and management

With local, conventional farmer's practices (FP) as the control and three integrated soil–crop system management (ISSM) practices at different nitrogen (N) application rates were established-ISSM-N1, ISSM-N2 and ISSM-N3, for improving rice yield and agronomic nitrogen use efficiency (NUE). A zero-N control (NN) was included to calculate the agronomic NUE and N_2O emission factors. In total, five field experimental treatments with four replicated field plots (6 m × 7 m) were established with a randomized block design in 2009. According to the local FP, the total N fertilizer application rate was 300 kg N ha^{-1} for the rice crop season and 180 kg N ha^{-1} for the wheat crop season as measured by farmer's application which usually used by conventional farmer's practice as usual. The ISSM strategies include N fertilizer splitting application and transplanting density as the main techniques improving rice yield and the NUE at the reduced N levels of the ISSM-N1 and ISSM-N2 with different yield targets. N was reduced by 25% and 10% for ISSM-N1 and ISSM-N2, respectively, and the corresponding total N application rate for the rice and wheat crop

Table 1
Integrated soil–crop system management (ISSM) practice establishment for the annual rice–wheat rotations in the two cycles of 2009 and 2010.

Practice	NN (zero-N)	FP (farmer's practices)	ISSM-N1 (N rate at 25% reduced)	ISSM-N2 (N rate at 10% reduced)	ISSM-N3 (N rate at FP rate)
Rice					
Chemical fertilizer application rate ($N:P_2O_5:K_2O:Na_2SiO_3:ZnSO_4$, kg ha^{-1})	0:90:120:0:0	300:90:120:0:0	225:90:120:0:0	270:90:120:0:0	300:108:144:225:15
Split N application ratio		6:2:0:2	5:1:2:2	5:1:2:2	5:1:2:2
Rapeseed cake manure (t ha^{-1})	0	0	0	0	2.25
Water regime	F-D-F-M	F-D-F-M	F-D-F-M	F-D-F-M	F-D-F-M
Planting density (cm)	20 × 20	20 × 20	20 × 15	20 × 15	20 × 15
Wheat					
Chemical fertilizer application rate ($N:P_2O_5:K_2O$, kg ha^{-1})	0:90:180	180:90:180	135:90:180	162:90:180	180:108:216
Split N application ratio		6:1:3	6:1:3	6:1:3	6:1:3
Seedling density (kg ha^{-1})	180	180	180	180	180

rotations was 225 and 135 kg N ha^{-1}, respectively for the ISSM-N1 and was 270 and 162 kg N ha^{-1}, respectively for the ISSM-N2. In addition to the N split and rice density techniques, more techniques (e.g., rapeseed cake in additional 112.5 kg N ha^{-1}, additional phosphorus, potassium, zinc and silicon) were comprehensively integrated at the conventional N application rate of the ISSM-N3 to exploit the rice yield and NUE potentials, with a total chemical N fertilizer application rate of 300 and 180 kg N ha^{-1} for the rice and wheat crops, respectively. Because the optimized ISSMs were mainly designed and developed for the rice crop, the management for the following wheat crop remained the same except for the corresponding total N reduction level. Details on each of the management practices of the five treatments are provided in Table 1.

During the two cycles of rice–wheat rotational systems, the rice cultivar of Changyou 3 and the wheat cultivar of Yangmai 5 were selected. According to local practices, rice was transplanted and wheat was sown one day after the basal fertilizer application. During the rice-growing season, one midseason drainage and final drainage before harvest were adopted; during the wheat-growing season, all plots received water via precipitation only. Urea, calcium superphosphate and potassium chloride fertilizer were applied to field for NPK requirement and dosage for crops at designed rates shown in Table 1. Fertilizers P, Si, Zn and manure (C/N = 8) were applied only as basal fertilizers for both crops at designed rates of each treatment. K was applied with two splits of 1:1 for the rice crop and as basal fertilizer for the wheat crop. N was splitted at designed rates of each treatment in four splits. All basal fertilizers were thoroughly incorporated into the soils within 15 cm depth by plowing and harrowing.

2.3. Chamber measurements of CH_4 and N_2O fluxes and total ecosystem respiration (Re)

The CH_4 and N_2O fluxes and ecosystem respiration (Re) were simultaneously measured using a static, opaque chamber method. In four replicate plots, fluxes were measured twice per week (every 3–4 days) during the rice-growing season and once per week during the wheat-growing season. Samples were collected more frequently after a precipitation event, fertilizer application and during the mid-season drainage and reflooding periods. One chamber was employed within each replicate plot. The chamber covered a field area of 0.25 m^2 and was placed on a fixed PVC frame on each plot. The chamber was wrapped with a layer of sponge and aluminum foil to minimize the air temperature changes inside the chamber during the period of sampling. The chamber was 0.5 or 1.1 m high, having been adapted for crop growth and plant height. For each flux measurement, four gas samples were collected from 9:00 to 11:00 am by a 20-ml syringe at 0, 10, 20, and 30 min after chamber closure. Sample sets were rejected unless they yielded a linear regression value of r^2 greater than 0.90. The average fluxes and standard deviations (SDs) of CH_4, N_2O and Re were calculated from four replicates. The seasonal amounts of CH_4, N_2O and Re emissions were sequentially linearly determined from the emissions between every two adjacent intervals of the measurements. The air temperature inside the chamber was monitored during gas collection and calibrated for flux calculation. Soil temperatures at a depth of 5 cm were monitored simultaneously with flux measurements, exhibiting a trend similar to that of the air temperature (Fig. 1).

Gas samples were analyzed for CH_4, N_2O and CO_2 concentrations by a gas chromatograph (Agilent 7890A, Shanghai, China) equipped with two detectors. N_2O was detected by an electron capture detector (ECD), and CH_4 was detected by a hydrogen flame ionization detector (FID). CO_2 was reduced with hydrogen to CH_4 in a nickel catalytic converter at 375 °C and then detected by the FID. The carrier gas was argon-methane (5%) at a flow rate of 40 ml min^{-1}. The temperatures for the column and ECD detector were maintained at 40 °C and 300 °C, respectively. The oven and FID were operated at 50 °C and 300 °C, respectively.

2.4. Components and measurements for SOC change and NECB of croplands

The apparent average conversion rate of organic carbon gain to soil organic carbon was reported to be 213 g kg^{-1} in paddy soil (Xie et al., 2010). Thus, the SOC change is estimated from the NECB using a coefficient of 0.213 for paddy soils in this study. In the same manner as Ciais et al. (2010), Smith et al. (2010) and Jia et al. (2012), we summarized the components for the NECB of short-plant croplands using intermittent chamber measurements:

$$\mathrm{NECB} = \mathrm{GPP} - \mathrm{Re} - \mathrm{Harvest} - \mathrm{CH_4} + \mathrm{Manure} \quad (1)$$

Here, GPP (gross primary production) is inferred from NPP (net primary production) via the NPP/GPP ratio method (Luyssaert et al., 2007). The NPP/GPP ratio of 0.58 is deduced from the resulting MODIS GPP and NPP products from Zhang et al. (2009).

Re (ecosystem respiration) is measured using the static, opaque chamber method.

Harvest includes straw removed and grain (measured directly at harvest and converted to carbon by crop-specific carbon contents of 0.42 and 0.49 for rice and wheat straw, respectively, and 0.38 and 0.39 for rice and wheat grain, respectively (Huang et al., 2007)). Harvest was removed out of the field for all the treatments during this study.

Manure is applied as rapeseed cake (5% N of dry weight) for the treatment ISSM-N3, as designated in Table 1.

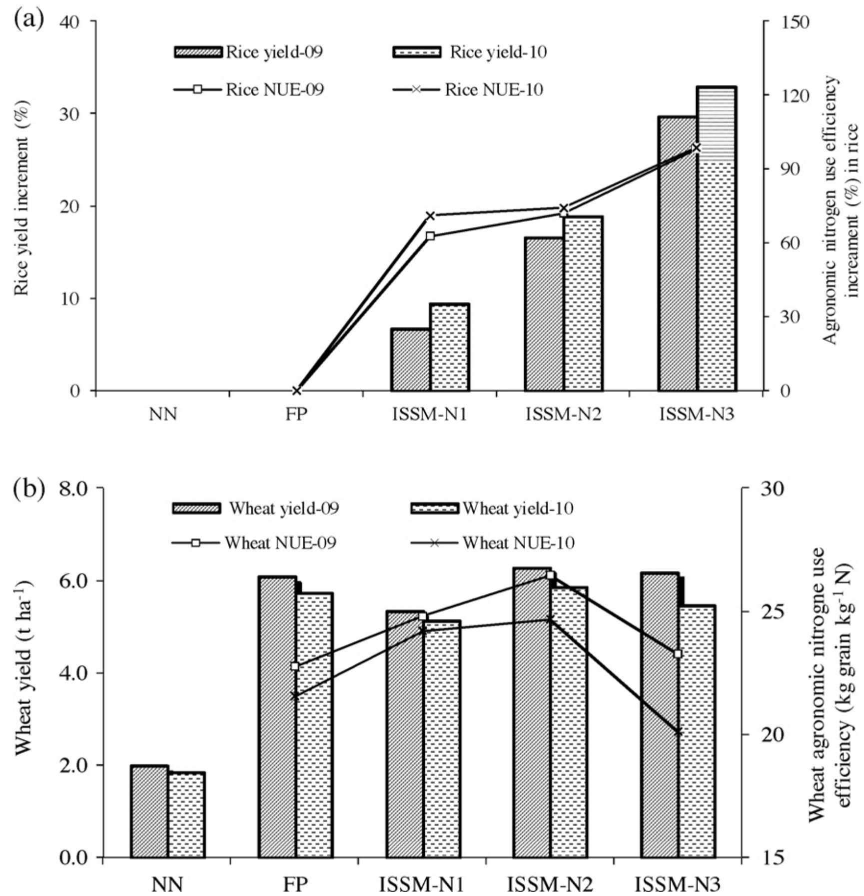

Fig. 2. (a) Rice grain yield and agronomic nitrogen use efficiency (NUE) increments and (b) wheat grain yield and agronomic NUE during the two rice-growing seasons of 2009 and 2010 in Changshu, China. See Table 1 for the treatment codes.

In croplands, NPP is estimated by Eq. (2) (Smith et al., 2010):

$$NPP = NPP_{grain} + NPP_{straw} + NPP_{root} + NPP_{litter} + NPP_{rhizodeposit} \quad (2)$$

The grain and straw biomass NPP is converted using the dry biomass weighed at harvest. Other components are estimated using allometric relationships according to Huang et al. (2007), in which the aboveground/root ratio was fixed at 1.0/0.1 for rice and 0.9/0.1 for wheat (Huang et al., 2007). Litter accounts for 5% of the aboveground and root dry biomass (Kimura et al., 2004), and rhizodeposits account for 15% (Mandal et al., 2008) and 18% (Gregory, 2006) of the total biomass for rice and wheat, respectively.

2.5. Methods and measurements for net GWP and GHGI of croplands

The net GWP of the cropland ecosystem equals the total CO_2 emission equivalents minus the SOC change in the cropland ecosystem.

$$\text{Net GWP} = 25 \times CH_4 + 298 \times N_2O - \frac{44}{12} \times \text{SOC change} \quad (\text{kg } CO_2 \text{ eq ha}^{-1}) \quad (3)$$

GHGI is related to grain yield, as described in Mosier et al. (2006) and Shang et al. (2010):

$$\text{GHGI} = \frac{\text{net GWP}}{\text{yield}} \quad (\text{kg } CO_2 \text{ eq kg}^{-1} \text{ grain yield}) \quad (4)$$

The harvested grain yield is expressed as the air-dried grain yield.

Considering the wide variation of the coefficient from organic amendment to SOC (Xie et al., 2010) and the fact that the NECB is not comparable with fresh amendments and made up of various sources, two additional cases were included for comparison and analysis. Thus three cases of results of net GWP and GHGI under three different assumptions were obtained: (1) all of the extra C remains in the system, i.e. a NECB-to-soil C coefficient of 1 over a long term and presented as net GWP1 and GHGI1; (2) none of the extra C stays in the system, i.e. ignore any changes in soil C over a long term and presented as net GWP0 and GHGI0; (3) 21.3% of the NECB stays in the system over a long term as the average coefficient from Xie et al. (2010) and presented as net GWP and GHGI.

2.6. Statistical analysis

The effects of blocks on CH_4, N_2O, CO_2 emissions and grain yield were compared at $p > 0.05$ in pre-analysis of data. Accordingly, the blocks were not included as a random effect in analysis followed by package SPSS 18.0 for Windows (SPSS Incorporated, United States) for calculating the two-way analysis of variance (ANOVA) and linear relationships. The *F*-test was applied to determine if there were significant differences among the practices, years or regression relationships at $p < 0.05$. Unless indicated otherwise, the differences were only considered when significant at $p < 0.05$. The average fluxes of CH_4, N_2O and CO_2 from the four replicates are plotted without standard deviation bars for clarity. We define an emission peak as a peak that was significantly higher than the previous and following fluxes.

Table 2
Two-way ANOVA for the effects of cultivation patterns (P) and cropping year (Y) on CH_4 and N_2O emissions, ecosystem respiration (Re), and rice and wheat grain yields for the two annual rice–wheat rotations of 2009 and 2010.

Crop season	Factors	df	CH_4 (kg C ha^{-1})			N_2O (kg N ha^{-1})			Re (t C ha^{-1})			Yield (t ha^{-1})		
			SS	F	P	SS	F	P	SS	F	P	SS	F	P
Rice	P	4	108,537	10.0	<0.001	1.73	7.79	<0.001	53.53	31.26	<0.001	129.26	278.90	<0.001
	Y	1	96,104	35.4	<0.001	0.57	10.27	<0.01	1.08	2.52	0.12	8.59	74.16	<0.001
	P × Y	4	13,867	1.3	0.3	0.24	1.10	0.38	0.76	0.25	0.77	1.31	2.82	<0.05
	Model	9	218,518	9.0	<0.001	2.55	5.09	<0.001	55.37	14.37	<0.001	139.16	133.45	<0.001
	Error	30	81,374			1.67			12.84			3.48		
Wheat	P	4	376.73	0.33	0.86	82.51	33.58	<0.001	85.04	33.67	<0.001	97.41	254.10	<0.001
	Y	1	345.80	1.20	0.28	220.81	359.52	<0.001	0.45	0.72	0.40	1.31	13.67	<0.001
	P × Y	4	773.87	0.67	0.62	64.98	26.45	<0.001	2.93	1.16	0.35	0.39	1.02	0.41
	Model	9	1496.40	0.58	0.58	368.29	66.763	<0.001	88.42	15.56	<0.001	99.11	114.91	<0.001
	Error	30	8661.97			18.42			18.94			2.88		
Rice–wheat	P	4	114,092	9.94	<0.001	99.29	51.77	<0.001	255.09	52.73	<0.001	423.15	604.27	<0.001
	Y	1	107,976	37.62	<0.001	198.74	414.47	<0.001	2.93	2.42	0.13	3.20	18.27	<0.001
	P × Y	4	13,240	1.15	0.35	69.17	36.06	<0.001	1.18	0.24	0.91	0.64	0.91	0.47
	Model	9	235,308	9.11	<0.001	366.20	85.09	<0.001	259.20	23.81	<0.001	426.99	271.00	<0.001
	Error	30	86,096			14.39			36.28			5.25		

3. Results and discussion

3.1. Rice production and agronomic nitrogen use efficiency (NUE)

The agronomic NUE in this study was calculated as the difference in grain yield between the treatment and NN plots and was divided by the N fertilizer rate (Fig. 2). The averaged grain yield from the FP plot was 8.5 t ha^{-1} for rice and 5.9 t ha^{-1} for wheat; the agronomic NUE was 9.0 kg grain kg^{-1} N for rice and 22.2 kg grain kg^{-1} N for the wheat crop. These agronomic NUE values for the rice crop are relatively low compared to values of 10.4–17.2 kg grain kg^{-1} N reported elsewhere (Peng et al., 2006), which were mainly due to the high N input at 300 kg N ha^{-1} for rice in this region as compared to the N rate of 60–120 kg N ha^{-1} in Peng et al. (2006).

During the two cropping cycles, the grain yields of both rice and wheat significantly varied with the cultivation pattern and years shown in Tables 2 and 3. Compared to the FP plot, rice grain yields significantly increased by 8.2%, 18% and 31% for ISSM-N1, ISSM-N2 and ISSM-N3, respectively. At the same time, the agronomic NUE significantly increased by 68%, 74% and 99% for the ISSM-N1, ISSM-N2 and ISSM-N3 plots, respectively, compared to the FP plot (Table 2 and Fig. 2a). Thus, the ISSM strategies were effective measures in improving the rice grain yield and NUE, and these findings revealed with the findings of Chen et al. (2011) and Zhang et al. (2011) on major crop of maize in North China. According to the ISSM practices, the N loss could be greatly reduced because of increased crop uptake. Because no ISSM strategy was developed for the wheat crop, the wheat grain yield and agronomic NUE did not increase. The wheat grain yield decreased significantly when the N fertilizer rate was reduced by 25% for the ISSM-N1 practice (Table 2 and Fig. 2a). All of these findings suggested that the ISSM in China is an effective way for future sustainable rice agriculture in terms of grain yield and NUE.

3.2. Net CH_4 fluxes during the two cycles of the annual rice–wheat rotation

During the two cycles of rice–wheat annual rotations of 2009 and 2010, the net CH_4 flux was significant during the rice-growing season but negligible during the wheat-growing season (Fig. 3a). During the rice-growing season, all the plots served as net sources of atmospheric CH_4. The highest CH_4 fluxes were detected at 51.1 mg C m^{-2} h^{-1} in 2009 and 38.7 mg C m^{-2} h^{-1} in 2010 for the ISSM-N3 plot (Fig. 3a). All treatments showed similar seasonal patterns of net CH_4 fluxes. The net CH_4 fluxes increased after transplantation (at a rate dependent on the amendment of organic manure) and decreased dramatically during the midseason drainage. After reflooding, the CH_4 fluxes increased again to a low emission peak and then decreased gradually to a negligible amount toward harvest (Fig. 3a). During the two cycles of rice–wheat rotation, the annual cumulative CH_4 emissions, on average, varied between 166 and 288 kg C ha^{-1} yr^{-1} (Table 3), and these values are comparable to those of previous findings (Cai et al., 2000; Huang et al., 2004; Yan et al., 2005; Zou et al., 2005a; Khalil, 2008). The highest cumulative CH_4 emission recorded was 288 kg C ha^{-1} yr^{-1} in the ISSM-N3 plot averaged over the two cycles of rice–wheat rotations (Table 3). Compared to the FP plot, the ISSM-N3 plot emitted 46% more CH_4 emissions in total, which is likely due to the application of the organic rapeseed cake manure (Tables 1 and 2) and is supported by previous reports (Naser et al., 2007; Zou et al., 2005a). Moreover, rice growth significantly increased in the ISSM-N3 and the resulting increase in soil C input likely contributed to the increase in CH_4 emissions. An obvious linear relationship among the CH_4 emission rates, rice NPP production and the NECB was established in this study (Fig. 4a and b), which could be explained by the fact that the rice plants served as a pathway for the CH_4 emissions and additional substrate for methanogens (Linquist et al., 2012a; Yan et al., 2005).

Averaged across the two years, the net CH_4 fluxes were negligible (2.49–9.84 kg C ha^{-1}) during the wheat-growing season, thus similar two-way ANOVA results were obtained between the rice-growing season and the total cycle (Tables 2 and 3). No obvious difference in the cumulative CH_4 emissions was found among the FP, the ISSM-N1 and the ISSM-N2 (Table 3). There was no correlation between the CH_4 emissions and N rate (Table 2). Previous reports on the influence of synthetic fertilizer on CH_4 emission rates from rice fields are inconsistent. Some studies suggested that the CH_4 emissions decreased with the application of inorganic fertilizer (Krüger and Frenzel, 2003; Zou et al., 2009), while others suggested an increase or no change (Cai et al., 2007). CH_4 emissions decreased by N fertilizers suggested the stimulation of methanotrophs in rice soils with intermittent drainage as reported by Banger et al. (2012). Linquist et al. (2012b) suggested that CH_4 emissions increased at low inorganic fertilizer N rate (average of 79 kg N ha^{-1}) while decreased at high N rates (average of 249 kg N ha^{-1}). The average CH_4 emission was significantly lower in the 2009 rice season than in the 2010 season ($p < 0.001$) (Table 2), which could be partly explained by the fact that the temperature during the elongation stage through the heading stage of the rice-growing season was significantly lower in 2009 than that in 2010 ($p < 0.001$) (Fig. 1).

Table 3
Seasonal CH_4 and N_2O emissions, ecosystem respiration (Re), and rice and wheat grain yields during the rice- and wheat-growing seasons in the two cycles of 2009 and 2010.

	Rice season				Wheat season			
Treatment	CH_4 (kg C ha^{-1})	N_2O (kg N ha^{-1})	Re (kg C ha^{-1})	Yield (t ha^{-1})	CH_4 (kg C ha^{-1})	N_2O (kg N ha^{-1})	Re (kg C ha^{-1})	Yield (t ha^{-1})
2009								
NN	91.50 ± 18.50	0.11 ± 0.15	5776 ± 273	5.62 ± 0.58	−2.76 ± 13.99	0.58 ± 0.10	3300 ± 325	1.99 ± 2.25
FP	135.78 ± 23.01	0.43 ± 0.18	7920 ± 1121	8.06 ± 0.17	−1.49 ± 10.27	7.70 ± 0.50	7503 ± 605	6.09 ± 5.64
ISSM-N1	128.93 ± 27.25	0.25 ± 0.16	8345 ± 499	8.60 ± 0.26	−4.27 ± 19.35	6.55 ± 1.39	6695 ± 617	5.34 ± 2.43
ISSM-N2	132.32 ± 37.29	0.28 ± 0.16	8529 ± 733	9.40 ± 0.18	13.36 ± 24.88	7.11 ± 1.10	7340 ± 245	6.28 ± 3.81
ISSM-N3	198.81 ± 91.48	0.93 ± 0.54	9136 ± 762	10.46 ± 0.28	6.82 ± 3.95	7.71 ± 1.48	6661 ± 1085	6.18 ± 2.86
2010								
NN	159.69 ± 31.53	0.48 ± 0.09	6175 ± 175	5.91 ± 0.36	5.32 ± 10.28	0.95 ± 0.26	3731 ± 412	1.86 ± 0.22
FP	246.65 ± 59.41	0.61 ± 0.22	8254 ± 897	8.86 ± 0.35	14.66 ± 17.37	1.35 ± 0.56	7224 ± 206	5.74 ± 0.24
ISSM-N1	198.50 ± 44.24	0.56 ± 0.17	8161 ± 236	9.70 ± 0.36	9.24 ± 13.04	1.17 ± 0.28	7782 ± 1097	5.13 ± 0.25
ISSM-N2	208.17 ± 69.91	0.66 ± 0.08	9168 ± 716	10.54 ± 0.20	6.32 ± 26.19	1.29 ± 0.22	6911 ± 1253	5.86 ± 0.17
ISSM-N3	364.79 ± 66.21	0.89 ± 0.25	9592 ± 426	11.78 ± 0.43	5.51 ± 17.70	1.41 ± 0.25	6916 ± 1115	5.48 ± 0.33
Average 2009–2010*								
NN	125.60 ± 20.61b	0.30 ± 0.07b	5975 ± 98c	5.77 ± 0.11e	1.28 ± 7.55a	0.75 ± 0.11b	3515 ± 327b	1.92 ± 0.22c
FP	191.21 ± 40.70ab	0.52 ± 0.07b	8087 ± 991b	8.46 ± 0.24d	6.59 ± 12.07a	4.53 ± 0.44a	7364 ± 206a	5.92 ± 0.38a
ISSM-N1	163.71 ± 27.64b	0.41 ± 0.05b	8253 ± 292b	9.15 ± 0.60c	2.49 ± 9.06a	3.86 ± 0.75a	7239 ± 623a	5.24 ± 0.25b
ISSM-N2	170.25 ± 49.76b	0.47 ± 0.11b	8849 ± 590ab	9.97 ± 0.13b	9.84 ± 24.90a	4.20 ± 0.59a	7125 ± 531a	6.07 ± 0.27a
ISSM-N3	281.65 ± 65.03a	0.91 ± 0.31a	9364 ± 227a	11.12 ± 0.11a	6.16 ± 7.94a	4.56 ± 0.78a	6789 ± 929a	5.83 ± 0.28a

* Mean ± SD, different letters within the same column for each item indicate significant difference at $p < 0.05$ by the Student's multiple range tests. See Table 1 for treatment codes.

3.3. N_2O emissions during the two cycles of annual rice–wheat rotation

During the two cycles of the rice–wheat annual rotations of 2009 and 2010, most of the N_2O was emitted during the wheat-growing season, and there were several small emission peaks during the rice-growing season (Fig. 3b), which is consistent with previous studies (Akiyama et al., 2005; Liu et al., 2010; Zou et al., 2005b). During the wheat-growing season, the peak rates of the N_2O fluxes were recorded as 1442 μg N m^{-2} h^{-1} for the ISSM-N2 plot in 2009 and 200 μg N m^{-2} h^{-1} for the ISSM-N3 plot in 2010 (Fig. 3b). Pulse N_2O emissions were observed in this study and have often been found in other studies (Deng et al., 2012). Though the chamber-based methods lack the temporal and spatial resolution required to follow the event driven nature of N_2O fluxes compared to the continuous measurements (Wagner-Riddle et al., 1997), the technique still provides valuable information for evaluating management practices (Pattey et al., 2007).

The seasonal and annual N_2O emission rates were significantly affected by cultivation practice patterns and years (Table 3). Relative to the FP plot, on average, the ISSM-N1 and the ISSM-N2 decreased the annual N_2O emissions by 15% and 8%, respectively (Table 2). The ISSM-N3 practices emitted 8% more N_2O because they received additional N via manure application compared to the FP practice (Tables 1–3). The total N input was clearly related to the N_2O emissions for all treatments during the rice- and wheat-growing seasons (Fig. 4c), which may be the reason for the differences among the practices. N_2O is produced naturally in the soil through nitrification and denitrification and depends on soil mineral N contents over the annual rotation (Yao et al., 2010). The N fertilizer input to facilitate crop production augments this production (Linquist et al., 2012).

Averaged across the treatments, the annual N_2O emission rates in 2009 were 4.60 kg N ha^{-1} yr^{-1} greater than the rates recorded in 2010 ($p < 0.001$) (Tables 2 and 3). Though the seasonal N_2O emission rates during the rice-growing season in 2010 were, on average, 0.24 kg N ha^{-1} greater than the rates recorded in 2009 (Table 2), the N_2O emissions during the wheat-growing season were the main contributor to the total N_2O emissions. The highest cumulative N_2O emission rates (7.71 kg N ha^{-1}) were recorded during the wheat-growing season in the ISSM-N3 plot in 2009 (Table 2). Higher N_2O emissions during the wheat-growing period occurred in the 2009 cycle than in the 2010 cycle, which was attributed to the rainfall events before fertilization and high rain intensity in 2009 (Figs. 1 and 3b). A previous study also reported that the key factor affecting N_2O emissions from agricultural soil was the soil water filled pore space (WFPS) (Dobbie and Smith, 2003). During the wheat-growing season, the total rainfall amounted to 107 mm in the 2010 cycle, which was 66% lower than the 315 mm reported in the 2009 cycle. Consequently, the WFPS was significantly lower (ranging from 42% to 70%, with a mean of 61%) in the 2010 cycle than that in the 2009 cycle (ranging from 63% to 84%, with a mean of 71%) (Fig. 5, $p < 0.001$).

The N_2O emission factor was averaged 0.08% during the rice-growing season (Tables 1 and 3), which was lower than the previous studies (0.35–0.68%) (Akiyama et al., 2005; Liu et al., 2010; Linquist et al., 2012a). Though higher than that estimated by Liu et al. (2010), the N_2O emission factor of 2.16% during the wheat growing season over 2009 and 2010 (Tables 1 and 3) fall within the range of 1.33–2.97% (Chen et al., 2008). The N_2O emission factor was, on average, estimated to be 0.87% over the whole annual rotation cycle in this study, which is extremely close to the estimates of the N_2O emission factor estimated by Liu et al. (2010) and Li et al. (2001). However, the annual N_2O emission factors in this study are generally lower than those of previous estimates in Chinese upland croplands (Yan et al., 2003; Zheng et al., 2004). The background N_2O emission of 1.05 kg N ha^{-1} from the NN plot in this study is comparable to the estimates by Yan et al. (2003) and within the lower range of Chinese croplands estimated by Gu et al. (2007), Liu et al. (2010) and Li et al. (2001).

3.4. Ecosystem respiration during the two cycles of annual rice–wheat rotation

Re can be measured by the opaque static chamber method (Jia et al., 2012). The CO_2 flux measured by the opaque chamber method is the total Re, which includes the respiration of plants and soil microorganisms. The maximum CO_2 emission rate, detected in the ISSM-N3 plot, was 991.5 mg C m^{-2} h^{-1} during the rice-growing season and 941.4 mg C m^{-2} h^{-1} during the wheat-growing season (Fig. 3c). The seasonal CO_2 emission rate was consistent between the two years (Table 2). The CO_2 fluxes remained positive during the two cycles of rice–wheat rotations, following the seasonal trends of plant growth and temperature change (Fig. 3c), which is consistent

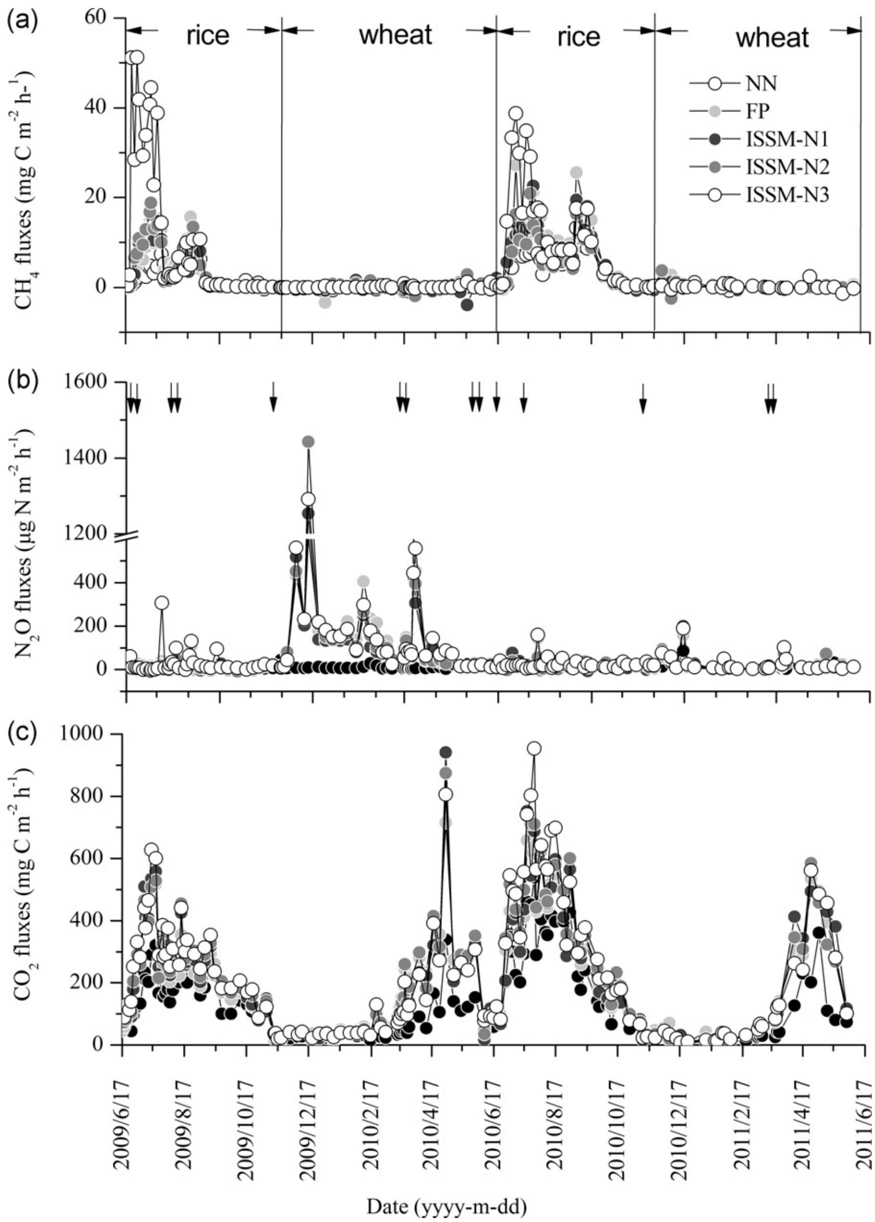

Fig. 3. Seasonal variations of (a) CH_4, (b) N_2O, and (c) ecosystem respiration CO_2 during the two cycles of rice–wheat rotations in 2009 and 2010 in Changshu, China. The arrow indicates N fertilization. See Table 1 for treatment codes.

with previous findings (Franzleubbers et al., 2002; Robertson et al., 2000).

The seasonal and annual cumulative CO_2 emission rates were quite different among cultivation practice patterns (Table 3). Averaged over the two crop seasons, the largest cumulative CO_2 emission rate was recorded in the ISSM-N3 plot (9.4 t C ha^{-1} for rice; 6.8 t C ha^{-1} for wheat), while the lowest rate was recorded in the NN plot (6.0 t C ha^{-1} for rice; 3.5 t C ha^{-1} for wheat). No obvious difference in CO_2 emission rates was found among the FP, the ISSM-N1 and the ISSM-N2 (Table 3). The Re during the rice season for the ISSM-N3 increased significantly by 16% compared with the FP plot mainly because of the higher biomass, which showed relatively good agreement with the results of Phillips and Podrebarac (2009).

3.5. NECB and SOC change

NECB refers to the total rate of organic carbon accumulation in (or loss from) ecosystems (Smith et al., 2010). The positive value of the NECB represents ecosystem carbon gain after harvest on crop seasonal scale. In accordance with the methods of Smith et al. (2010), we adopted the GPP and Re approaches to estimate the carbon balance in the vegetable production (Jia et al., 2012) and in the rice–wheat rotations (Table 4). Over the two cycles of rice–wheat rotations in 2009 and 2010, all treatments, except for the NN plot, indicated slight carbon gains for the fertilization plots (range of 0.416–3.13 t C ha^{-1} yr^{-1} with an average of 1.58 t C ha^{-1} yr^{-1}). The small carbon loss for the NN plot was the result of the lower yield and biomass production (Tables 3 and 4) and a lack of organic manure application (Table 1).

The NECBs were significantly affected by the management practices (Table 4). No obvious difference was found between the FP and either the ISSM-N1 or the ISSM-N2, though the ISSM-N2 practices produced significantly higher NECBs than did the ISSM-N1 practices. The NECBs increased significantly by 2.31 t C ha^{-1} yr^{-1} for the ISSM-N3 plot compared to the FP plot (Table 4). Grain yield as the major harvest was the dominant component of the NECB. The ISSM practices aiming for a higher grain yield also gained a

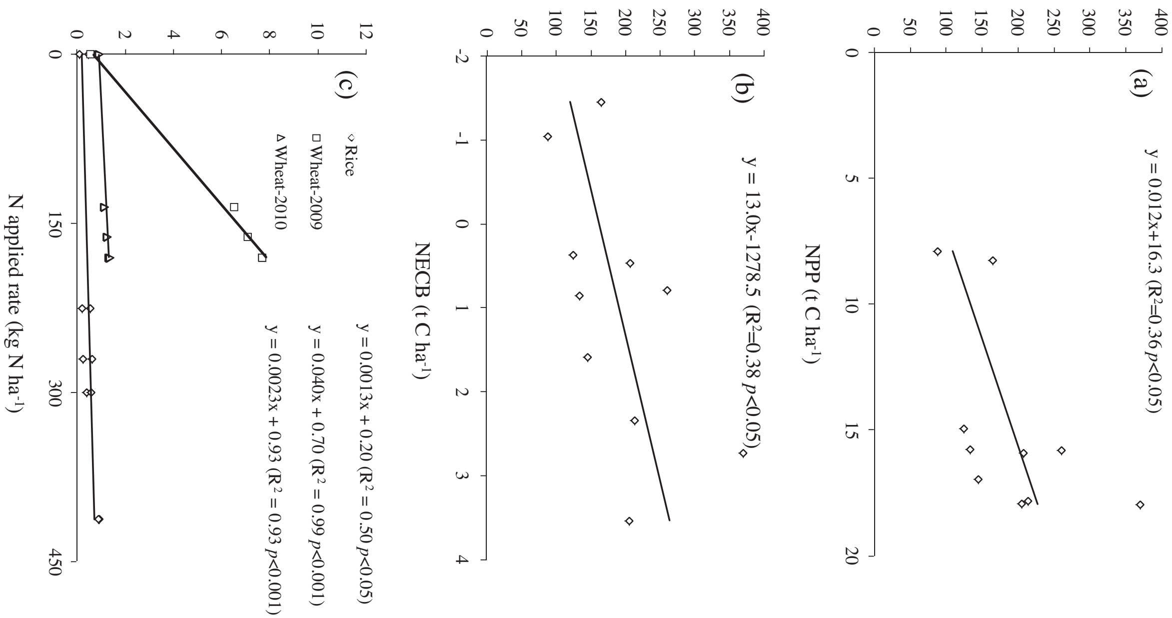

Fig. 4. Correlations between (a) the net carbon budget (NECB), (b) the net primary production (NPP) and the cumulative methane (CH_4) emissions and (c) N_2O emissions and total N rate during the two cycles of rice–wheat rotations in 2009 and 2010 in Changshu, China.

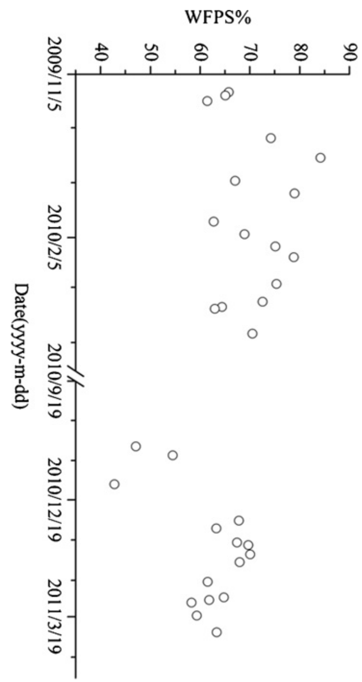

Fig. 5. Soil water-filled pore space (WFPS) along the N fertilization periods during the 2009 and 2010 wheat-growing seasons of the two rice–wheat rotation cycles in Changshu, China.

Table 4
NECB and its main components for the two cycles of annual rice–wheat rotations of 2009 and 2010 (t C ha^{-1} yr^{-1}).

Treatment	2009[a]				2010				Average over 2009 and 2010 cycles			
	NECB[b]	NPP[c]	Harvest	Re	NECB	NPP	Harvest	Re	NECB	NPP	Harvest	Re
NN	−1.05 ± 0.06c	7.87 ± 0.05d	5.41 ± 0.04d	9.08 ± 0.10b	−1.46 ± 0.24d	8.27 ± 0.24c	5.69 ± 0.17c	9.91 ± 0.59b	−1.25 ± 0.10d	8.07 ± 0.10d	5.55 ± 0.07d	9.49 ± 0.27b
FP	0.85 ± 0.73b	15.7 ± 0.42c	10.7 ± 0.28c	15.4 ± 1.44a	0.786 ± 0.61bc	15.8 ± 0.20b	10.7 ± 0.14b	15.5 ± 0.83a	0.820 ± 0.67bc	15.8 ± 0.29c	10.7 ± 0.19c	15.5 ± 1.09a
ISSM-N1	0.37 ± 0.43bc	14.9 ± 0.24c	10.2 ± 0.16c	15.0 ± 0.86a	0.463 ± 0.57c	15.9 ± 0.15b	10.8 ± 0.10b	15.9 ± 1.29a	0.416 ± 0.43c	15.4 ± 0.19c	10.5 ± 0.13c	15.5 ± 0.90a
ISSM-N2	1.58 ± 0.52b	16.9 ± 0.28b	11.5 ± 0.18b	15.9 ± 0.90a	2.33 ± 0.78ab	17.8 ± 0.15a	12.1 ± 0.10a	16.1 ± 1.42a	1.96 ± 0.49ab	17.3 ± 0.17b	11.8 ± 0.11b	16.0 ± 0.74a
ISSM-N3	3.53 ± 0.79a	17.9 ± 0.31a	12.2 ± 0.21a	15.8 ± 1.51a	2.73 ± 0.50a	17.9 ± 0.14a	12.3 ± 0.09a	16.5 ± 1.23a	3.13 ± 0.35a	17.9 ± 0.21a	12.2 ± 0.14a	16.2 ± 1.05a

[a] Mean ± SE, different letters within the same column for each item indicate significant difference at $p < 0.05$ by the Student's multiple range test.

[b] NECB = NEP – harvest – CH_4 + manure; NEP, net ecosystem production. NEP = GPP – Re; GPP, gross primary production; Re, ecosystem respiration. NPP/GPP = 0.58; NPP, net primary production.

[c] $NPP = NPP_{grain} + NPP_{shoot} + NPP_{root} + NPP_{litter} + NPP_{rhizodeposit}$.

higher NECB (Table 4), which supports the assumptions by Burney et al. (2010) and Smith et al. (2010). Carbon lost from the ecosystem in other forms such as leaching, fire and erosion is manageable and negligible in the rice croplands (Trumbore, 2006; Zheng et al., 2008).

A conversion of NECB into SOC was adopted since only part of the NECB would eventually become soil carbon sequestration while major part of the NECB would decompose on long term timescale, either as CO_2 in soil respiration or methane under flooded condition. Although the NECB is not comparable with fresh amendments and made up of various sources, we are roughly assigning the average coefficient from Xie et al. (2010) in this case over a long term that 21.3% of the NECB stays in the system as SOC (Table 5). The SOC sequestration rate for the FP plot (0.17 t C ha^{-1} yr^{-1}), though lower than previous estimates for some double rice-cropping paddy soils (Lu et al., 2009; Shang et al., 2010), was supported by the recent work of Liao et al. (2009), which reported the provincial mean SOC sequestration rate in Jiangsu to be 0.16 ± 0.09 t C ha^{-1} yr^{-1} from 1982 to 2004, where the dominant ecosystem is annual upland rice crop rotation. The SOC sequestration rate ranged from −0.27 t C ha^{-1} yr^{-1} for the NN plot to 0.67 t C ha^{-1} yr^{-1} for the ISSM-N3 plot, which is comparable to the estimated range of 0.28–0.47 t C ha^{-1} yr^{-1} for the topsoil mean SOC covering all upland and paddy soils in eastern China (Sun et al., 2009). Additionally, the SOC sequestration rates for the FP and ISSMs plots fall within the SOC sequestration rate of 0.13–2.20 t C ha^{-1} yr^{-1} estimated by Pan et al. (2004) for paddy soils in China. The adapted approach in this study is applicable to trials requiring multiple field plots of a short-plant ecosystem on crop seasonal time scale. Thus, this approach may provide a methodological alternative to fill the measurement gap for quantifying SOC changes derived from the NECBs of fragmented terrains at high temporal and spatial resolutions.

Compared to the FP plot, the ISSM-N3 significantly increased the SOC rate in this study, with a rate of 0.67 t C ha^{-1} yr^{-1}; the ISSM-N2 had higher SOC rate at 0.42 t C ha^{-1} yr^{-1} than the ISSM-N1 at 0.089 t C ha^{-1} yr^{-1} though both practices showed no obvious differences in SOC rate with the FP plot. The main difference was induced by the enhanced incorporation of manure and crop residue associated with higher crop productivity. This finding supports the DNDC model projection by Li et al. (2006) that the national average SOC sequestration rate would increase from 0.48 to 0.70 t C ha^{-1} yr^{-1} with increased crop residue incorporation rates from 15% to 50%.

3.6. *Net global warming potential (GWP) and greenhouse gas intensity (GHGI)*

By definition, the net GWP is estimated by the net exchange of gases (i.e., N_2O and CH_4) and SOC changes (Table 5). In terms of N_2O and CH_4, the net GWPs were mainly attributed to CH_4 emissions in the rice-growing season and, to a less extent, to the N_2O emissions during the wheat-growing season as averaged over the two cycles of the 2009 and 2010 rice–wheat rotations. The CH_4 emissions dominated the net GWPs, accounting for 74–99% of the net GWPs in the two cycles of rice–wheat rotations (Table 5). GHGI was introduced to express the relationship between net GWP and grain yield. The GHGIs ranging from 0.41 to 0.74 kg CO_2eq kg^{-1} grain in this study (Table 5) were comparable to previous estimates of 0.24–0.74 kg CO_2eq kg^{-1} grain from rice paddies with midseason drainage and organic manure incorporation (Qin et al., 2010; Li et al., 2006) but were lower than the DNDC model estimates for the continuous waterlogged paddies (3.22 kg CO_2eq kg^{-1} grain) (Li et al., 2006).

During the two cycles of the 2009 and 2010 rice–wheat rotations, the contribution of the SOC change to the net GWPs was important, particularly for ISMM-N2 (19.1%) and ISMM-N3 (20.4%) while the contribution was less for ISMM-N1 (4.6%) and FP (8.0%).

Table 5
Mean annual CH_4 and N_2O emissions and δSOC rates and net GWP and GHGI over the two cycles of annual rice–wheat rotations in 2009 and 2010.

Treatment	CH_4 (kg CH_4 ha^{-1} yr^{-1})	N_2O (kg N_2O ha^{-1} yr^{-1})	δSOC[a] (t C ha^{-1} yr^{-1})	Grain yield (t ha^{-1} yr^{-1})	Net GWP[b] (t CO_2eq ha^{-1})	Net GWP_0 (t CO_2eq ha^{-1})	Net GWP_1 (t CO_2eq ha^{-1})	GHGI[c] (kg CO_2eq kg^{-1} grain)	$GHGI_0$ (kg CO_2eq kg^{-1} grain)	$GHGI_1$ (kg CO_2eq kg^{-1} grain)
NN	169 ± 32c[d]	1.65 ± 0.16c	−0.27 ± 0.02d	7.69 ± 0.12d	5.70 ± 0.85cA	4.72 ± 0.84cB	9.30 ± 0.82aA	0.74 ± 0.11aB	0.61 ± 1.11abB	1.21 ± 0.11aA
FP	264 ± 47b	7.94 ± 0.68ab	0.17 ± 0.14bc	14.38 ± 0.44c	8.36 ± 1.96abA	8.96 ± 1.21bA	5.58 ± 1.19bB	0.58 ± 0.14abA	0.62 ± 0.09abA	0.39 ± 0.09bB
ISSM-N1	222 ± 47bc	6.71 ± 1.13b	0.089 ± 0.092c	14.39 ± 0.22c	7.21 ± 1.63bcA	7.54 ± 1.42bA	6.01 ± 1.42bA	0.50 ± 0.12abA	0.53 ± 0.11bA	0.42 ± 0.10bA
ISSM-N2	240 ± 68bc	7.34 + 1.02b	0.42 ± 0.10ab	16.04 ± 0.33b	6.66 ± 1.78bcA	8.19 ± 1.71bA	1.00 ± 1.18cB	0.41 ± 0.11bA	0.51 ± 0.10bA	0.06 ± 0.09cB
ISSM-N3	384 ± 86a	8.60 ± 0.83a	0.67 ± 0.07a	16.94 ± 0.19a	9.71 ± 2.19aA	12.15 ± 2.33aA	0.68 ± 2.20cB	0.57 ± 0.13abA	0.72 ± 0.14aA	0.04 ± 0.13cB

[a] NECB derived SOC change equal to 0.213 × NECB (Xie et al., 2010).

[b] Net GWP (kg CO_2eq ha^{-1}) = 25 × CH_4 + 298 × N_2O − 44/12 × SOC change; net GWP_0 (kg CO_2eq ha^{-1}) = 25 × CH_4—C × 16/12 + 298 × N_2O—N × 44/28; net GWP_1 (kg CO_2eq ha^{-1}) = 25 × CH_4 + 298 × N_2O − 44/12 × NECB.

[c] GHGI (kg CO_2eq kg^{-1} grain) = net GWP/grain yields; $GHGI_0$ (kg CO_2eq kg^{-1} grain) = net GWP_0/grain yields; $GHGI_1$ (kg CO_2eq kg^{-1} grain) = net GWP_1/grain yields.

[d] Mean ± SD, different lower case letters within the same column indicate significant difference at $p < 0.05$ by Student's multiple range test; for items of net GWP and GHGI, different capital letters within the same row indicate significant difference at $p < 0.05$ by Student's multiple range test.

Moreover, the NN plot acted as an important source of soil CO_2 with negative 21.3% (Table 5). Thus, it is recommended for inclusion of SOC change into the net GWP evaluations.

Regarding the wide range of the apparent coefficient from NECB to SOC, results indicate that SOC played an important role in the net GWP and GHGI evaluation among various treatments (Table 5). In particular, when the coefficient of 1 was adopted, i.e. not considering the difference between NECB and SOC, comparison results of net GWP1 and GHGI1 among various treatments were completely different and even reversed. However, the comparison results of net GWP0 and GHGI0 among various treatments remained similar trends with those of net GWP and GHGI though differed to some extent. Therefore, considerate selection of the coefficient is essential for correct assessment on net GWP and GHGI. Site-specific or source material-specific measurement of the coefficient is desired for better constraint.

In the case of the coefficient being 0.213 from NECB to SOC as reported as the average value for paddy soil (Xie et al., 2010), differences in net GWP or GHGI were found among cultivation practice patterns over the two cycles of rice–wheat rotations (Table 5). Compared to the net GWPs (8.36 t CO_2eq ha^{-1} yr^{-1}) and GHGI (0.58 kg CO_2eq kg^{-1} grain) from the FP, the ISSM-N1 and the ISSM-N2 reduced both the net GWPs and GHGIs. The net GWPs decreased by 14% in the ISSM-N1 plots and by 20% in the ISSM-N2 plots; the GHGI also decreased in the ISSM-N1 and ISSM-N2 plots compared to the FP plot, with the lowest GHGI value (0.41 kg CO_2eq kg^{-1} grain) obtained in the ISSM-N2 plot. This finding is consistent with the estimation by Burney et al. (2010) that the net effect of higher yields has offset emissions by as much as 590 Gt CO_2eq since 1961. These results indicated that GHG mitigation can be simultaneously achieved with improved food production and NUE. Thus, the nationwide agricultural initiative of the ISSM strategy for higher grain yields and enhanced NUE is effective and practically applicable.

Although produced similar GHGIs, the ISSM-N3 increased net GWPs by 16% compared to the FP (Table 5), indicating that more research is required on the ISSM for mitigating GHGs to further increase both the grain yield and the NUE in paddy field. However, while it did not lead to more GHGIs, the ISSM-N3 is still advocated for future food security. The ISSM strategies with different yield targets provide solutions for feeding the growing world population and therefore deserve considerable attention.

4. Conclusions

A complete perspective was proposed in this study to assess the integrated soil–crop system management (ISSM) on net GWP and GHGI. This study provided a method to estimate the SOC change derived from the NECB on the crop seasonal or annual time scale. Slightly less carbon loss occurred during the rice–wheat rotation (−1.25 t C ha^{-1} yr^{-1}) for the NN plot, while obvious carbon gains occurred (0.416–3.13 t C ha^{-1} yr^{-1}) for the ISSM practices and the FP. Over the two cycles of the 2009 and 2010 rice–wheat rotations, the net GWPs were mainly attributed to CH_4 emissions in the rice-growing season and, to a less extent, to N_2O emissions during the wheat-growing season. The contribution of the SOC change was significant, particularly for ISSM-N2 and ISSM-N3 plots. Compared to the FP plot, the ISSM-N1 and ISSM-N2 plots both produced less net GWPs and GHGIs, indicating that GHG mitigation can be simultaneously achieved with food production and resource-use efficiency. The ISSM-N3 produced similar GHGIs and increased net GWPs by 16% compared to the FP, indicating that more research on soil–crop managements is required for mitigating GHGs to further increase grain yield and NUE in rice agriculture. ISSM strategies are an effective way to accommodate the growing population.

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